Light and invisible

Underground transmission with HVDC Light

Dag Ravemark, Bo Normark

When power must be transmitted over long distances, overhead lines (OHL) have long been the prevailing technology. The costs and performance of buried cables made them unattractive as an alternative.

The advent of HVDC Light® is bringing about a huge change. Whereas buried cables are not suitable for long-distance high-voltage AC transmissions, the different behavior of DC fundamentally changes this.

The high costs of burying cables which has long made this mode unattractive is also losing ground as an argument. The combination of environmental concerns over the impact of overhead lines and the availability of new cost-saving technologies is leading to a re-think. Underground cables are now more attractive than ever before.

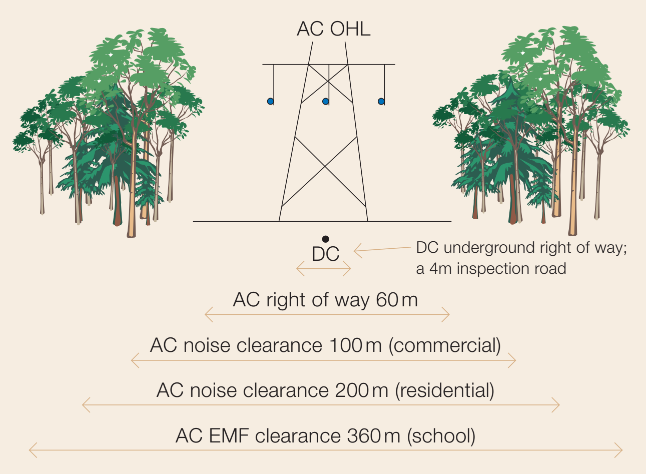
Grid flexibility

For over a century electrical transmission systems have been based mainly on overhead transmission lines (OHL). The main reason for this has been the cost advantage when compared to high-voltage underground transmission.

Recent studies suggest the cost premium of underground transmission is in the range of 5–15 times the traditional overhead transmission alternative. But this comparison is already dated. Two main factors are affecting the paradigm:

- Environmental restrictions are increasing the costs and implementation time for overhead transmission.
- Technological development significantly reduces the cost of underground transmission.

1 Land use comparison for HVDC Light® and AC OHL transmission.



Consequences of environmental restrictions

There are several reasons why underground HVDC cables have a better environmental profile than overhead HVAC lines.

Land use

An HVDC cable uses significantly less land than an overhead HVAC line. The right-of-way for a 400 kV OHL can be a 60 m wide strip 1 where no buildings/high trees are allowed whereas an underground DC cable needs at most a 4 m wide inspection road on top of it. For AC OHL the amount of land required for a 400 km transmission is 2,400 hectares (1 hectare = 10,000 m²). However only 160 hectares are required for DC cable (< 6 percent).

Audible noise

Restrictions on land use stretch beyond the immediate right-of-way. Audible noise from transmission line corona – most noticeable when conductors are wet in foggy weather conditions – might restrict buildings close to OHL. The width of this "noise corridor" depends on local noise ordinance as well as on the design and voltage of the line. Noise objections from neighbors make it more difficult to obtain permits. An underground DC cable naturally has no audible noise emission.

EMF

Magnetic and electrical fields can also restrict the use of land close to an OHL. In several countries a precautionary policy vis-à-vis magnetic fields is in force. The Swedish National Electrical Safety Board and the Dutch Ministry of Housing and Environment both suggest a 0.4 µT safety level for 50 Hz magnetic fields from transmission lines. This level corresponds to field levels normally encountered in city environments today. In contrast to an AC line, the field for a DC cable is static (non-radiant). Applying the same precautionary policy as for AC would not call for the provision of any "EMF corridor" around an underground DC cable. The field immediately above the cable is far less than the earth's natural magnetic field.

2 Effect of proximity of overhead line on property values (in Finland).

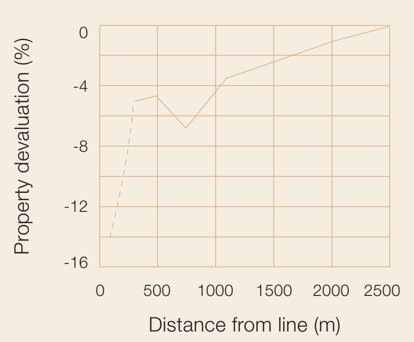


Table 1 Comparison of material usage

Material	DC underground	AC OHL
Aluminium	3.3 kg	2.1 kg
Copper	1.4 kg	
PVC	2.3 kg	
PEX	6.1 kg	
Steel		100.0 kg
Ceramics		0.3 kg
Concrete		376.3 kg
Total	**13.1 kg**	**478.8 kg**

Right-of-way as a loss of CO_2 sink

Growing forests are considered CO_2 sinks because trees convert carbon dioxide from the atmosphere into carbon stored in the form of wood and organic soil matter. A forest can absorb 9.2 tons of CO_2 per hectare per year. Building a 400 km, 400 kV overhead transmission line through an area that is 75 percent forest represents a loss of a carbon sink of 16,780 tons of CO_2 per year.

HVDC Light® technology was introduced in 1997 with a small test installation of 3 MW. Since then, both cables and converters have progressed dramatically in both size and performance.

Material use

The material intensity of an AC OHL is higher than a DC cable. The statistical material use per meter of transmission is compared in Table 1.

Using lifecycle assessment (LCA) to analyze the "cradle to grave" material impact, the DC cable has an environmental impact of 64.5 kg of CO_2-equivalents per meter and the AC OHL has an impact of 365.4 kg of CO_2-equivalents per meter. In other words, the material used in the DC cable has only 17.6 percent the environmental impact of the AC OHL.

Aesthetics – Property value

Several studies have shown that property values are reduced close to OHL. For example, a study carried out in the United Kingdom showed the value of detached properties a distance of 100m from OHL were 38 percent lower than comparable properties. A Finnish study showed that the reduction is proportional to the distance from the line 2.

Assuming that every 500 m along the 400 km line there is:

- One property 500 m from the OHL (with 8 percent value reduction).
- Two properties 1000 m from the OHL (with 4 percent value reduction).
- Three properties 2000 m from the OHL (with 2 percent value reduction).

If an average property is valued at $ 150,000, the reduction in property value along the 400 km OHL then amounts to a staggering $ 25 million.

Electrical losses

When HVDC Light® underground transmission is used inside an AC-grid, the transmission system can be operated in a more optimal way leading to lower electrical losses. The losses in the HVDC line are equivalent to the loss reduction of the AC grid, ie, the HVDC line is considered to transmit electricity "without" losses. The more efficient operation of a transmission system with HVDC can be attributed to two causes: the average higher voltage level in the AC grid and the reduction of reactive power flows.

For example, on a 350 MW transmission (50 percent utilization) there are no HVDC losses whereas HVAC losses amount to 5 percent. This means the operator has 76,650 MWh more electricity to sell each year with an HVDC connection.

The overall electrical losses[1] can be translated into 45,990 tons of CO_2 emitted per year.

Power system stability

HVDC systems can never become overloaded, and they offer additional benefits through their ability to control power flow and voltage 3. HVDC can be very effective in damping power oscillations, as well as avoiding or limiting cascading system disturbances, particularly when connecting two points inside the same AC-grid, ie, in parallel with AC-lines: an HVDC Light® converter is excellent at generating or consuming reactive power.

Technical characteristics of underground transmission system

When planning traditional overhead transmission lines, it is better to choose high voltage lines for transmission over large distances because not only can transmission capacity be increased but losses are also reduced. However, for AC transmission in underground cables the situation is somewhat different. If the voltage is increased, the reactive power absorption of the cable increases so that its technical maximum length is reduced rather than increased. The laws of physics in this case then work against long AC transmission. Today's experience of cable transmission suggests a maximum transmission distance of about 60 km for a 345 kV AC underground cable.

Reasons why underground HVDC cables have a better environmental profile than overhead HVAC lines include land use, audible noise, EMF, material use, and power systems stability.

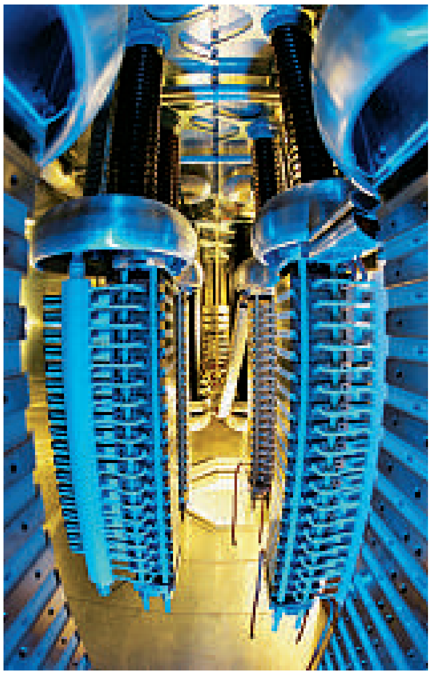
HVDC Light®, a new transmission system designed for underground transmission

This technology is based on some key components:

- Extruded cable technology
- Converter technology
- Control and protection technology

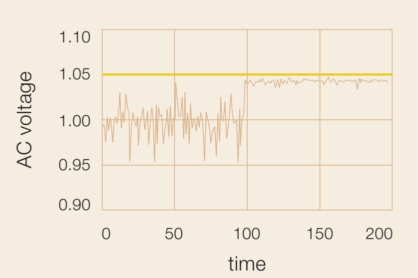
Voltage source converters cause less stress on the cables than conventional HVDC converters and this has enabled the development of extruded cables for HVDC. The extruded cable has some significant advantages over traditional mass impregnated cables. It:

- Is completely oil free.
- Has low weight.
- Is very flexible and this simplifies handling during installation.
- Has very simple prefabricated joints.



3 HVDC improves the stability of AC networks.

Bus voltage Maximum voltage



4 HVDC Light® product matrix.

Available 2000 Available 2004 Available 2006

DC Voltage	500 A	1000 A	1500 A
+/- 80 kV	90 MW	180 MW	280 MW
+/- 150 kV	170 MW	350 MW	500 MW
+/- 300 kV	350 MW	700 MW	1000 MW

Footnote

[1] Using the OECD average of 600 kg CO_2/MWh for electricity.

Grid flexibility

5 Construction of Murraylink HVDC Light® (Australia).

Voltage source converters also show significant advantages over traditional HVDC converters such as:

- Dramatically smaller size. Typically they are half the height and their footprint is 25 percent smaller.
- Superior voltage and reactive power control reduces the risk of blackouts.
- They act as a "firewall" for network disturbances and block the cascading trips that occur in AC systems[2].
- They can operate in very weak networks and do not require network reinforcements.
- They reduce down time after outages with their "black start" capability.

New high-speed control and protection technology makes it possible to fully utilize the inherent benefits of the voltage source converters.

Technical development of HVDC Light® systems

HVDC Light technology was introduced to the market in 1997 with a small test installation of 3 MW. Since then, both cables and converters have progressed dramatically in both size and performance. Today the largest system in service is a 330 MW system operating at ±150 kV. A 350 MW system is currently under construction. The converter design has been refined by the adoption of new switching schemes that reduce the number of components and cut the converter losses by 60 percent.

In contrast to traditional HVDC, an HVDC Light® system is highly modularized and makes greater use of semiconductors. The product matrix shown in 4 highlights available modules.

Increased environmental pressure on overhead transmission lines is both raising total costs and increasing the risk for substantial project delays.

Cable installation techniques

A crucial element in underground transmission is the cable installation technique. In the Murraylink project in Australia, 5 and 6, a very successful installation was implemented using modified pipeline installation equipment. Up to 3 km of cable was successfully installed per day. The total cost of laying the 170 km cable system amounted to the very reasonable sum of about AU$ 10 million ($ 7.6 million). HVDC Light cables have relatively low weight (typically < 10 kg/m), making its installation similar to that of fibre-optic cables: the equipment used for trenching and the depth at which the cables are laid is comparable (1 to 1.5 m below the surface).

Cost comparison Overhead lines – Underground transmission

The new HVDC technology has, as already mentioned, some unique characteristics particularly when it comes to increasing network security. This means before a strict cost comparison is performed, a needs evaluation is required. Some key checkpoints are listed in Table 2.

Table 2 HVDC suitability checklist

☐ Need for power transmission 50–1000 MW
☐ Need for accurate and fast control
☐ Distance more than 100 km
☐ Difficult to obtain permits for OHL
☐ Asynchronous networks
☐ Weak AC network
☐ Risk for dynamic instability
☐ Power quality issues
☐ Need for grid black start capability
☐ Need for high availability although occurrence of thunderstorms, wind storms/hurricanes or heavily icing conditions may apply
☐ Need for low maintenance
☐ Need for small footprint
☐ Risk of low harmonic resonances
☐ Need for fast voltage an reactive power control to enhance network security

Footnote

[2] See "HVDC: A 'firewall' against disturbances in high-voltage grids", Lennart Carlsson, ABB Review 3/2005 pp 42–46.

If at least three of these conditions are fulfilled it is likely that an HVDC Light® system will offer a very attractive solution. If, however, OHL permits are difficult to obtain, then this reason alone is sufficient to warrant an HVDC Light® solution.

In the following paragraphs, two examples currently being studied are presented.

Case 1,700 MW over 400 km

It is assumed this case fulfils at least five of the criteria outlined in Table 2, such as:

- The need for 50–1000 MW.
- Transmission distance is greater than 100 km.
- Difficulty to obtain permits for OHL.
- Risk of dynamic instability.
- Need for fast voltage and reactive power control to enhance network security.

A comparison of the direct investment cost shows the following span:
The direct investment cost for HVDC Light® option including converters, cables and their installation is in the range of $275–$420 million. The breadth of this range is primarily due to differences in installation costs and local market conditions.

For the AC overhead option there is an even greater span in cost. A study made by ICF consultancy in 2001 shows a huge variation in costs from country to country. Using these data, the direct investment cost for the AC overhead option gives a cost range of $130–$440 million for the line including installation and substations.

At the direct investment cost level the price for the underground alternative is between 0.6 and 3.2 times the overhead option. This is quite a difference from the normally anticipated 5–15 times.

Furthermore, other factors should also be considered, for example:

- Additional investments in equipment to manage voltage and reactive power control in the AC case.
- Losses (both cases).
- Costs for permitting the overhead solution.
- Cost for permission and construction time (both cases).
- Increased transmission capacity in the existing AC grid (HVDC case).
- Loss of property value.

When these factors are included in the evaluation, the competitiveness of the HVDC alternative increases. Assume, for example, the following realistic additional factors for the overhead option:

- Additional reactive compensation: $25 million.
- Loss of property value: $25 million.
- Value of increased transmission capacity in existing AC grid: $50 million.

Applying these factors raises the price tag of the AC alternative to between $230 million and $540 million, and that of the underground option to between $275 million and $420 million. The costs of the two alternatives are quite comparable and local factors determine which option is the most advantageous.

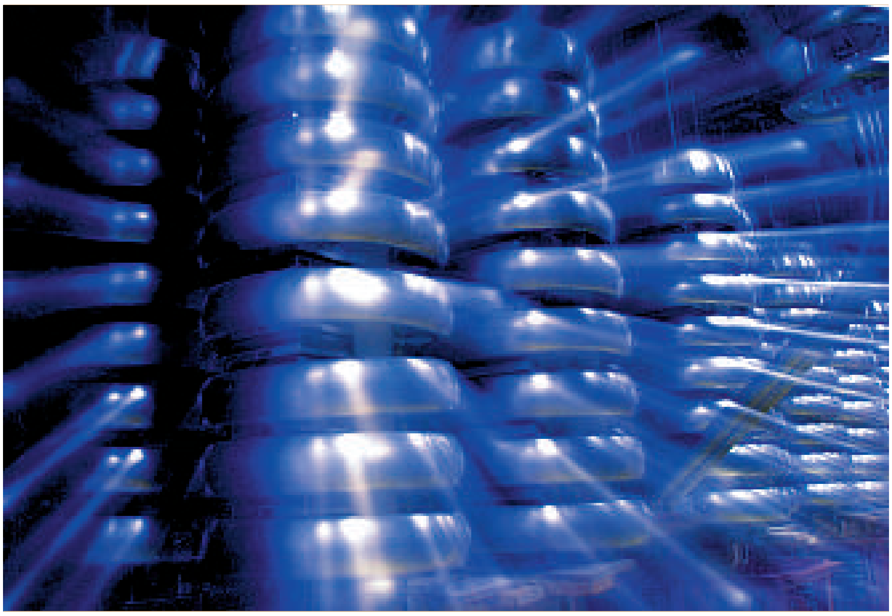
Case 2,350 MW over 100 km

A similar exercise for this case results in a direct investment cost for the HVDC option of between $110 million and $150 million, whereas the AC overhead version costs vary between $40 million and $90 million. The relative direct investment cost of the HVDC solution is in the range of 1.2–3.75 times that of an OHL. The application of the additional factors discussed above will again reduce the cost difference between the alternatives.

Conclusions

Increased environmental pressure on overhead transmission lines is both raising total costs and increasing the risk for substantial project delays. New HVDC technology in the form of HVDC Light® has made underground options technically feasible and economically viable. This is especially so if the new grid investment is driven by security of supply issues. The conventional view that an underground link will cost 5 – 15 times its overhead counterpart must be revised. Depending on local conditions, it is realistic that the costs for an underground high-voltage line are equal to that of traditional overhead lines.

6 HVDC Light® valve.



Dag Ravemark
ABB Cororate Research
Västerås, Sweden
dag.ravemark@se.abb.com

Bo Normark
ABB Power Technologies
Zürich, Switzerland
bo.normark@se.abb.com